THE RESPONSE OF VEGETATION DISTRIBUTION, ECOSYSTEM PRODUCTIVITY, AND FIRE IN CALIFORNIA TO FUTURE CLIMATE SCENARIOS SIMULATED BY THE MC1 DYNAMIC VEGETATION MODEL

WHITE PAPER

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

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The California Climate Change Center (CCCC) is sponsored by the PIER program and coordinated by its Energy-Related Environmental Research area. The Center is managed by the California Energy Commission, the Scripps Institution of Oceanography at the University of California at San Diego, and the University of California at Berkeley. The Scripps Institution of Oceanography conducts and administers research on climate change detection, analysis, and modeling; and the University of California at Berkeley conducts and administers research on economic analyses and policy issues. The Center also supports the Global Climate Change Grant Program, which offers competitive solicitations for climate research.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, these reports receive minimal editing, and the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

For more information on the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier/ or contact the Energy Commission at (916) 654-5164.

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Abstract

The objective of this study was to dynamically simulate the response of vegetation distribution, carbon, and fire to three scenarios of future climate change for California. Under all three scenarios, Alpine/Subalpine Forest cover declined with increased growing season length and warmth, while increases in the productivity of evergreen hardwoods with increased temperature led to the displacement of Evergreen Conifer Forest by Mixed Evergreen Forest. The simulated responses to changes in precipitation were complex, involving not only the effect on vegetation productivity, but also changes in tree-grass competition mediated by fire. Grassland expanded, largely at the expense of Woodland and Shrubland, even under the relatively cool and moist PCM-A2 climate scenario where increased woody plant production was offset by increased wildfire. Increases in net primary productivity (NPP) under the PCM-A2 scenario contributed to a simulated carbon sink of about 800 Tg for California by the end of the century. Declines in net primary productivity under the two warmer and drier GFDL scenarios, most evident under the GFDL-A2 scenario, were offset by reduced carbon losses to decomposition and fire consumption, producing a net carbon sink of about 150 and 300 Tg under the GFDL-A2 and GFDL-B1 scenarios respectively. Total annual area burned in California increased under all three scenarios, ranging from 9%–15% above the historical norm by the end of the century. Regional variation in the simulated changes in area burned was largely a product of changes in vegetation productivity and shifts in the relative dominance of woody plants and grasses. Annual biomass consumption by fire by the end of the century was about 18% greater than the historical norm under the more productive PCM-A2 scenario. However, by the end of the 21st century, biomass consumed by fire was below or near normal under the GFDL-A2 and GFDL-B1 scenarios, respectively, after several periods of above-normal fire during which grassland expanded into woodlands forming new biome boundary locations. The larger grassland regions annually produced more area burned, but with somewhat less actual biomass being consumed than under current conditions.

1.0 BACKGROUND

California is one of the most climatically and biologically diverse areas in the world. There is more diversity in the state's land forms, climate, ecosystems, and species than in any comparably sized region in the United States (Holland and Keil 1995). This diversity of habitats sustains a greater level of species diversity and endemism than is found in any other region of the nation (Davis et al. 1998). Much of California's biological wealth is threatened by the state's burgeoning population and the consequent impacts on the landscape. Throughout the state, natural habitats have been and continue to be altered and fragmented, endangering the state's biological diversity (Barbour et al. 1993).

In the future, global climate change will increasingly interact with and intensify the pressures of a growing population on the natural ecosystems of California. It is not possible to accurately predict the response of the natural systems to global climate change through direct experimentation. The physical extent, complexity, and expense of even a single-factor experiment for an entire ecosystem is usually prohibitive (Aber et al. 2001). However, analyses of the sensitivity of natural ecosystems to climate change can be made using ecosystem models that integrate information from direct experimentation.

In previous studies, the MC1 Dynamic Vegetation Model generated simulations of the response of vegetation distribution, ecosystem productivity, and fire to the observed historical climate and to several scenarios of potential future climate change for California (Lenihan et al. 2003, Hayhoe et al. 2005). The results of the simulations for the historical climate compared favorably to independent estimates and observations. The general response to increasing temperatures under all future climate scenarios was characterized by a shift in dominance from needle-leaved to broad-leaved lifeforms and by increases in vegetation productivity, especially in the relatively cool and mesic regions of the state. The simulated responses to changes in precipitation were complex, involving not only the effect on vegetation productivity, but also changes in tree-grass competition mediated by fire. The increasing trends in simulated fire area under all scenarios were primarily a response to changes in vegetation biomass. In the present study, MC1 simulations were generated under three new future climate scenarios for California.

2.0 METHODS

2.1. The Model

MC1 is a dynamic vegetation model (DVM) that simulates lifeform mixtures and vegetation types; ecosystem fluxes of carbon, nitrogen, and water; and fire disturbance. MC1 is routinely implemented (Daly et al. 2000; Bachelet et al. 2000, 2001b; Aber et al. 2001; Lenihan et al. 2003) on spatial data grids of varying resolution (i.e., grid cell sizes ranging from 900 m^2 to about 2500 km^2) where the model is run separately for each grid cell (i.e., there is no exchange of information across cells). The model reads climate data at a monthly time-step and calls interacting modules that simulate biogeography, biogeochemistry, and fire disturbance.

2.1.1. Biogeography Module

The biogeography module simulates the potential lifeform mixture of evergreen needleleaf, evergreen broadleaf, and deciduous broadleaf trees, and C3 and C4 grasses. The tree lifeform mixture is determined at each annual time-step by locating the grid cell on a two-dimensional gradient of annual minimum temperature and growing season precipitation. Lifeform dominance is arrayed along the minimum temperature gradient from more evergreen needleleaf dominance at relatively low temperatures to more deciduous broadleaf dominance at intermediate temperatures to more broadleaf evergreen dominance at relatively high temperatures. The precipitation dimension is used to modulate the relative dominance of deciduous broadleaved trees which is gradually reduced to zero towards low values of growing season precipitation. Mixtures of C3 vs. C4 grasses are determined by reference to their relative potential productivity during the three warmest consecutive months. Potential grass production by lifeform is simulated as a function of soil temperature using equations from the CENTURY model (Parton et al. 1987). The tree and grass lifeform mixtures together with wood and grass biomass simulated by the biogeochemistry module are used in a rule-base to determine which of twenty-two possible potential vegetation types occurs at the grid cell each year.

2.1.2. Biogeochemistry Module

The biogeochemistry module is a modified version of the CENTURY model (Parton et al. 1994) which simulates plant productivity, organic matter decomposition, and water and nutrient cycling. Plant productivity is constrained by temperature, effective moisture (i.e., a function of soil moisture and potential evapotranspiration), and nutrient availability. In this study, simulated vegetation productivity was assumed to be unconstrained by nutrient availability. The simulated effect of increasing atmospheric CO_2 is to increase maximum potential production and to decrease transpiration (thus reducing the constraint of effective moisture on productivity). Trees compete with grasses for soil moisture, light, and nutrients. Competition for water is structured by rooting depth. Trees and grasses compete for soil moisture in the upper soil layers where both lifeforms are rooted, while the deeper-rooted trees have sole access to moisture in deeper layers. Grass productivity is constrained by light availability in the understory which is reduced as a function of tree leaf carbon. Parameterization of the tree and grass growth processes in the model is based on the current lifeform mixture, which is updated annually by the biogeography module. For example, an increase in annual minimum temperature that shifted the dominance of evergreen needle-leaved trees to co-dominance with evergreen broadleaved trees would trigger an adjustment of tree growth parameters (e.g., the optimum growth temperature) that would, in turn, produce a modified tree growth rate.

2.1.3. Fire Disturbance Module

The MC1 fire module simulates the occurrence, behavior, and effects of fire. The module consists of several mechanistic fire behavior and effect functions (Rothermel 1972; Peterson and Ryan 1986; van Wagner 1993; Keane et al. 1997) embedded in a structure that provides two-way interactions with the biogeography and biogeochemistry modules. Live crown structure and fuel loading in several size classes of both dead and live fuels are estimated using lifeform-specific allometric functions of the different carbon pools. The moisture content of each dead fuel size-class is estimated as a function of antecedent weather conditions averaged over a period of days dependent on size-class. The moisture content of each live fuel class is a function of the soil moisture content to a specific depth in the profile. Fuel moisture and distribution of the total fuel load among different size-classes determine potential fire behavior estimated using the Rothermel (1972) fire spread equations.

The rate of fire spread and fireline intensity are the model estimates of fire behavior used to simulate fire occurrence and effects. The occurrence of a fire event is triggered by thresholds of fire spread, fine fuel flammability, and coarse woody fuel moisture (given a constraint of just one fire event per year). The thresholds were calibrated to limit the occurrence of simulated fires to only the most extreme events. Large and severe fires account for a very large fraction of the annual area burned historically (Strauss et al. 1989). These events are also likely to be least constrained by heterogeneities in topography and fuel moisture and loading that are poorly represented by relatively coarse-scale input data grids (Turner and Romme 1994).

The direct effect of fire in the model is the consumption and mortality of dead and live vegetation carbon which is removed from (or transferred to) the appropriate carbon pools in the biogeochemistry module. This direct effect is a function of the simulated fraction of the cell burned, fireline intensity, and tree canopy structure. The fraction of the cell burned depends on the simulated rate of fire spread and the time since the last fire event relative to the current fire return interval simulated for the cell. Higher rates of spread and longer intervals between fires generally produce more extensive fire events in the model. Live carbon mortality and consumption within the area burnt are functions of fireline intensity and the tree canopy structure (i.e., crown height, crown length, and bark thickness). Dead biomass consumption is simulated using functions of fire intensity and fuel moisture that are fuel-class specific.

Fire effects extend beyond the direct impact on carbon and nutrient pools to more indirect and complex effects on tree vs. grass competition. Fire tends to tip the competitive balance towards grasses in the model because much, or all, of the grass biomass consumed regrows in the year following a fire event. Woody biomass consumed or killed is more gradually replaced. A greater competitive advantage over trees promotes greater grass biomass which, in turn, produces higher fine fuel loadings and changes in the fuel bed structure that promote greater rates of spread and thus more extensive fire.

2.2. The Climate Data

The climate data used as input to the model in this study consisted of monthly time series for all the necessary variables (i.e., precipitation, minimum and maximum temperature, and vapor pressure) distributed on a 100 km^2 resolution data grid for the state of California. Spatially distributed monthly time-series data for historical (1895–2003) precipitation, temperature, and vapor pressure already existed at a 100 km^2 resolution. This dataset was developed from a subset of climate data generated by VEMAP (Kittel et al. 2004) and from observed California station data interpolated to the data grid by the PRISM model (Daly et al. 1994).

To construct spatially distributed climate time-series datasets for the potential future climatic periods (2004–2100) of our simulations, we used coarse-scale monthly output generated by two general circulation models (GCMs)—the Geophysical Fluid Dynamics Laboratory (GFDL) model and the National Center for Atmospheric Research (NCAR) parallel climate model (PCM). Both are state-of-the-art GCMs that include the influence of dynamic oceans and aerosol forcing on the atmosphere. Both GCM models were run from the 1800s to 1995 using observed increases in greenhouse gas concentrations, and into the future using two different emission scenarios (the relatively high-emissions A2 scenario and the low-emissions B1 scenario). Using a methodology that is an accepted norm for creating higher resolution climate scenarios for impact studies, we downscaled the four coarse-scale GCM scenarios to the 100 km^2 resolution (10 x 10 km). The steps in the development of the scenarios were as follows:

1. For each climate variable, monthly averages were calculated for the 1961–1990 GCM-simulated climate for each coarse-scale GCM grid cell over California.
2. At each GCM grid cell and for each future simulation month, "deltas" were calculated between the long-term average for each variable (from step 1) and the value for the "target" month taken from the GCM-simulated time series (deltas were calculated as differences for temperature variables, and as ratios capped at 5 for precipitation and vapor pressure).
3. The deltas for each variable were interpolated to a 100 km^2 resolution data grid using a bilinear interpolation procedure.
4. The interpolated deltas were applied back to a 100 km^2 resolution grid of climate means observed from 1961 to 1990 to create a high-resolution, gridded time series of possible future weather based on the coarse-grid GCM output.

3.0 RESULTS

3.1. The Response of Vegetation Distribution to the Future Climate Scenarios

The response of vegetation class distribution under the three future climate scenarios was determined by comparing the distribution of the most frequent vegetation type simulated for the 30-year historical period (1961–1990) against the same for the last 30 years (2071–2100) of the future scenarios (Figures 1–3). The simulated response of the vegetation classes in terms of changes in percentage coverage (Figure 4) was surprisingly similar under the three future climate scenarios. There was agreement on the direction of change (i.e., decrease or increase in coverage) for all but the Desert class, and the amounts of change were comparable for several of the vegetation classes. However, these similarities in the response of class coverage were often the net result of very different responses to each scenario in terms of the spatial distribution of vegetation classes as discussed below.

Significant declines in the extent of Alpine/Subalpine Forest were simulated under all three scenarios, especially under the warmest GFDL-A2 scenario. At high-elevation sites, the model responded to longer and warmer growing seasons, which favored the replacement of Alpine/Subalpine forest by other vegetation types.

Evergreen Conifer Forest declined under all scenarios, but the largest declines were simulated under the warmer and drier GFDL scenarios. Much of the simulated loss of this type was due to replacement by Mixed Evergreen Forest with increases in temperature, but reductions in effective moisture and increases in fire also resulted in losses of Evergreen Conifer Forest to Woodland, Shrubland, and Grassland. The decline in this type to Mixed Evergreen Forest under the cooler and wetter PCM-A2 scenario was largely offset by gains in the semi-arid regions of the Modoc Plateau and Central Coast where Conifer Forest advanced primarily into Shrubland.

Mixed Evergreen Forest increased in extent under all three scenarios. Increases in temperature enhanced the productivity of the mixed evergreen lifeform over the evergreen conifer lifeform, converting Evergreen Conifer Forest to Mixed Evergreen Forest. The expansion of this type was particularly significant under the PCM-A2 scenario, in which higher levels of effective moisture generally promoted the expansion of forest.

Mixed Evergreen Woodland and Shrubland declined under all three scenarios. Under the warm and drier GFDL scenarios, replacement of these two types, primarily by Grassland, was due to reductions in effective moisture and increased fire. Under the cooler and wetter PCM-A2 scenario, the decline in Woodland and Shrubland was due not only to encroachment by the forest types, but also by Grassland.

Expansion of Grassland under the warmer and drier GFDL scenarios was largely due to reductions in effective moisture. But Grassland gained in extent even under the cooler and wetter PCM-A2 scenario, especially in the semi-arid regions of the state. Here higher levels of effective moisture favored increased productivity of both woody lifeforms and grass. However, increases in grass biomass translated to more fine flammable fuels in the fire disturbance module, promoting more fire that in turn reduced the competitiveness of the woody lifeforms, resulting in the expansion of grasslands.

The Desert type was reduced in extent by the encroachment of Grassland under the wetter PCM-A2 scenario, but increased at the expense of Grassland under the drier GFDL scenarios.

3.2. The Response of Ecosystem Productivity to the Future Climate Scenarios

There was a general increasing trend in simulated total ecosystem net primary productivity (NPP) over the future period under the relatively cool and wet PCM-A2 scenario, and a general decreasing trend under the warmest and driest GFDL-A2 scenario (Figure 5a). However, there was considerable interannual variability in the future trend of NPP under all three scenarios, and even under the GFDL-A2 scenario there were periods when NPP was higher than normal (i.e., higher than the simulated mean annual NPP for the historical 1895–2003 period).

Net biological production (NBP) is the balance between carbon gained by the ecosystem via net primary productivity, and carbon lost from the ecosystem via decomposition and consumption by fire. The trend in cumulative NBP under the cooler and wetter PCM-A2 scenario (Figure 5b) showed a fairly steady increase over the course of the future period, resulting in the accumulation of about 800 Tg of new ecosystem carbon in California by the end of the century. And despite the general decline in net primary productivity under the GFDL scenarios, the model still predicted a net accumulation of about 150–300 Tg of new carbon by the end of the century under these scenarios. The general decline in NPP under the GFDL scenarios, most evident under the A2 emission scenario, was partially offset by reduced rates of litter and soil carbon decomposition under the drier conditions. There were also reductions in biomass consumption by fire near the end of the 21st century, accompanying a shift towards greater dominance of grass lifeforms. Under these drier scenarios, woodlands stressed by drought were consumed by fire, causing increases in biomass consumed earlier in the century, as they were converted to grasslands. Unlike woody plants, grasses largely regenerate biomass in the year following a fire, but burn more frequently causing increases in fire area, but with little biomass actually being consumed. Grasses also allocate a greater proportion of NPP to below-ground carbon stocks which are protected from fire.

3.3. The Response of Fire to the Future Climate Scenarios

There was a general increasing trend in simulated total annual area burned in California over the future period under each of the three climate scenarios (Figure 6a). All three future trends were characterized by considerable interannual variability. But for nearly every year, total area burned was greater than the simulated mean total annual area burned over the 1895–2003 historical period. By the end of the century, predicted total annual area burned ranged from 9% to 15% greater than normal.

Predicted trends in annual total biomass burned (Figure 6b) were strongly linked to the simulated trends in NPP (Figure 5a) over the future period. Greater than normal NPP produced more fuel under the cooler and wetter PCM-A1 scenario, and biomass consumption was about 18% greater than the historical norm by the end of the century. Under the warmer and drier GFDL scenarios, lower NPP produced less fuel, and biomass consumed was at, or below, the historical norm by the end of the century; however, after a transitional period of increased biomass consumed when the drought-stressed woodlands were being replaced by grasslands.

Summer months were warmer and persistently dry across California under all three scenarios, so drier-than-normal fuels were a pervasive factor in the higher-than-normal annual total area burned simulated by the model. However, spatial variation in the simulated changes in area burned under each scenario (Figure 7) was largely a product of changes in vegetation productivity and in the competitive balance between woody plants and grasses. Under all three scenarios, the greatest increases in annual area burned were simulated along the central and south coasts, in the northern Great Valley, on the Modoc Plateau, and along the eastern edge of the Sierra Nevada. These are semi-arid regions where ecosystems are delicately poised between woody plant and grass dominance. Here the response of the model to decreased effective moisture under the GFDL scenarios was an increase in the dominance of the more drought-tolerant grasses. And although the response to moderate increases in effective moisture under the PCM-A2 was increased productivity of both lifeforms, increases in grass biomass translated to more fine flammable fuels in the model, promoting more fire that in turn reduced the density of the woody lifeforms. So under all three scenarios, the response of the model in these semi-arid regions was characterized by a shift towards more grass-dominated vegetation (Figures 1–3), which in turn promoted more frequent fire and higher rates of spread, and thus more annual area burned.

4.0 DISCUSSION

The results of the three new MC1 simulations for California, like those generated under other future climate scenarios (Lenihan et al. 2003, Hayhoe et al. 2005), demonstrate certain ecosystem sensitivities and interactions that are likely to be features of the response of both natural and semi-natural systems (e.g., managed forests and rangelands) to a relatively certain rise in temperature and less certain changes in precipitation. An increase in temperature could increase vegetation productivity given adequate moisture availability, especially in cooler regions of the state. An increase in temperature could also alter forest composition by increasing the competitiveness of evergreen hardwood species which are less tolerant of low winter temperatures than conifers (Woodward 1987). The model results indicate fire will play a critical role in the adjustment of semi-arid vegetation to altered precipitation regimes, be it slowing or limiting the encroachment of woody vegetation into grasslands under wetter conditions, or hastening the transition from woody communities to grassland under drier conditions. The model results also suggest that changes in fire and shifts in the relative dominance of woody and grass lifeforms could buffer the effect of different climatic perturbations on total ecosystem carbon storage. Under a wetter climate, increased carbon storage with increased vegetation productivity could be limited by greater losses to wildfire. Under a drier climate, decreased carbon storage with the decreased vegetation productivity could be limited by decreased rates of decomposition and a shift towards greater dominance of grass lifeforms which are better adapted to more frequent fire and are more effective contributors to soil carbon stocks.

While none of the MC1 simulations for California should be taken as predictions of the future, it is evident from the results that all the natural ecosystems of California, whether managed or unmanaged, are likely to be affected by changes in climate. Changes in temperature and precipitation will alter the structure, composition, and productivity of vegetation communities, and wildfire may become more frequent and intense. The incidence of pest outbreaks in forests stressed by a changing climate could act as a positive feedback on the frequency and intensity of fire. Nonnative species preadapted to disturbance could colonize altered sites in advance of native species, preventing the already problematical redistribution of natives across a landscape highly fragmented by land-use practices.

Considerable uncertainty exists with respect to regional-scale impacts of global warming. Much of this uncertainty resides in the differences among different GCM climate scenarios and assumed trajectories of future greenhouse gas emissions as illustrated in this study. However, California is in a transitional location between the very wet Northwest and the very dry Southwest. Although global precipitation is expected to increase under global warming, minor uncertainties in shifts in the stormtracks that separate these wet and dry regions could result in either wetter or drier conditions, rendering regional precipitation patterns especially difficult to forecast for California.

In addition, models of ecosystem impacts to climate change can always be improved through careful testing and enhancement of model processes. Nevertheless, the results of this and previous studies underscore the potentially large impacts of climate change on California ecosystems, and the need for further use and development of dynamic vegetation models under various ensembles of climate change scenarios.

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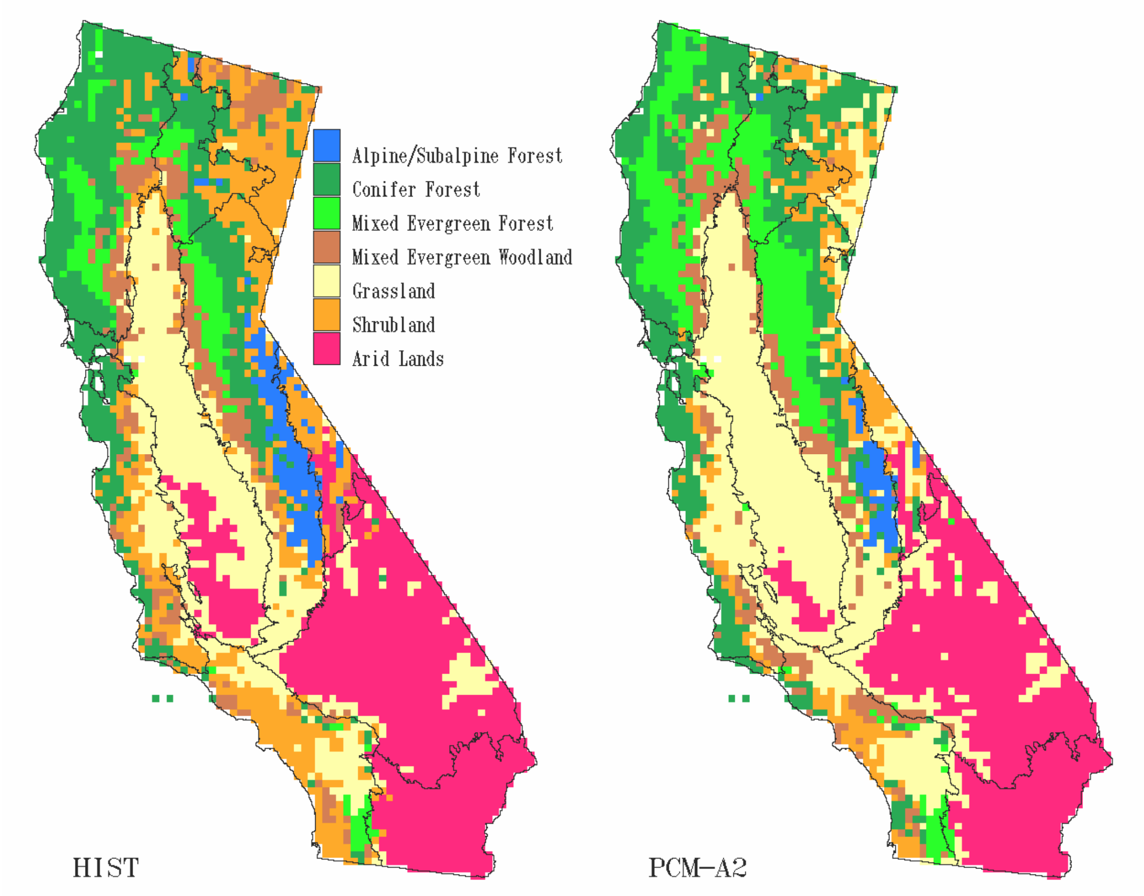

Figure 1. Distribution of the vegetation classes simulated for the historical (1961–1990) and PCM1-A2 future period (2070–2099). The vegetation class mapped at each grid cell is the most frequent class simulated during the time period.

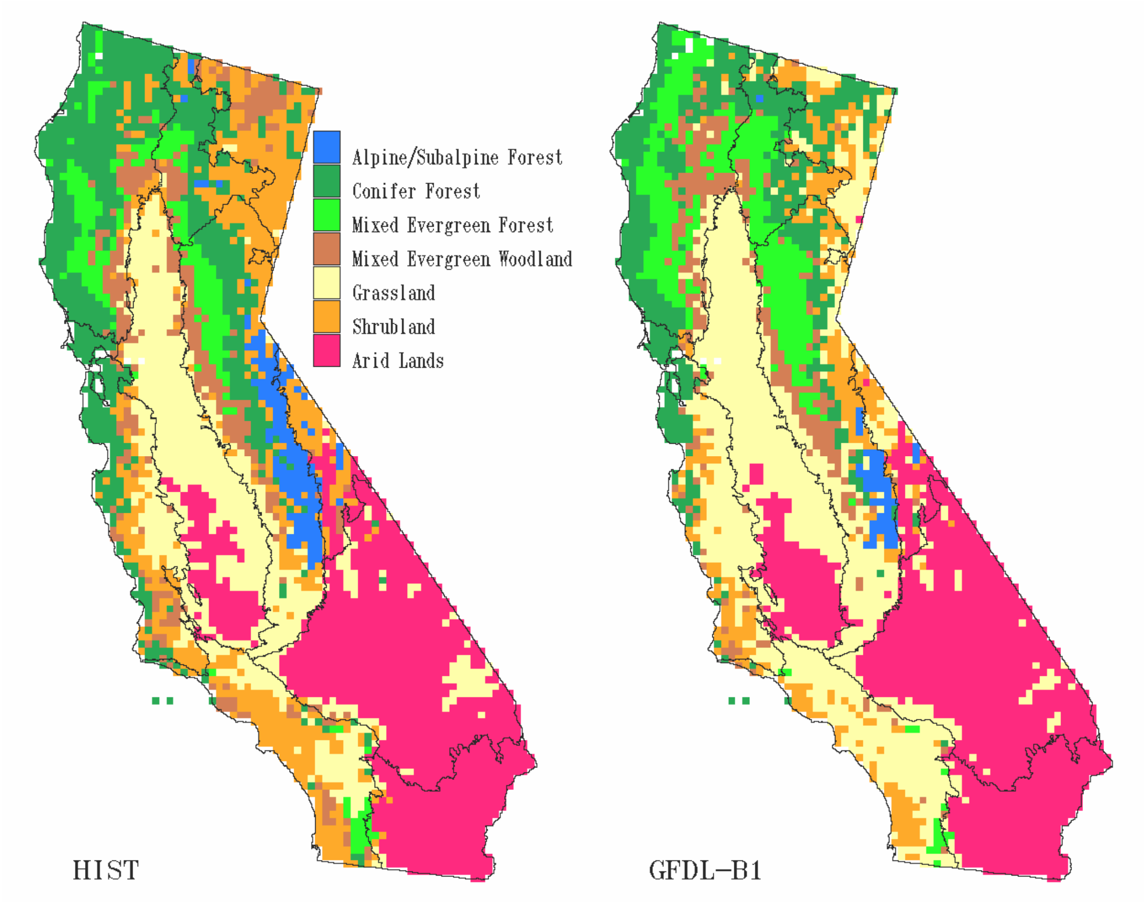

Figure 2. Distribution of the vegetation classes simulated for the historical (1961–1990) and GFDL-B1 future period (2070–2099). The vegetation class mapped at each grid cell is the most frequent class simulated during the time period.

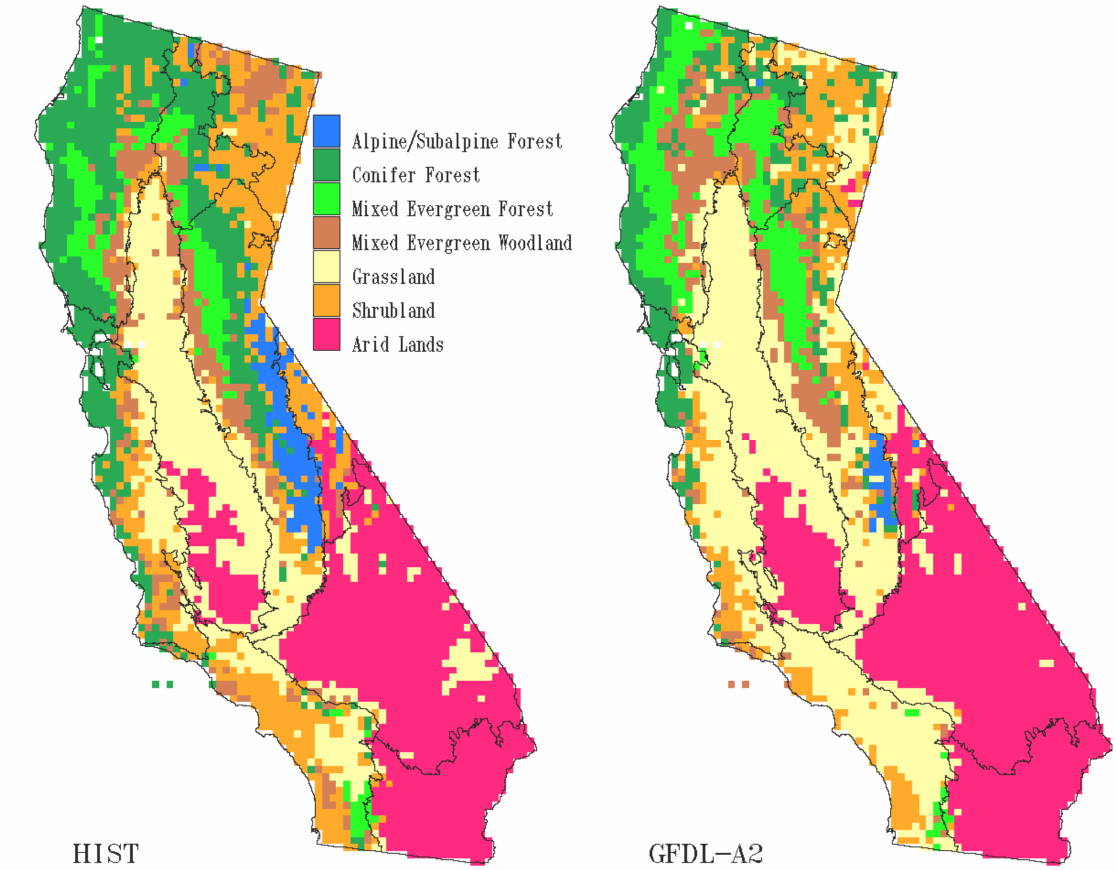

Figure 3. Distribution of the vegetation classes simulated for the historical (1961–1990) and GFDL-A2 future period (2070–2099). The vegetation class mapped at each grid cell is the most frequent class simulated during the time period.

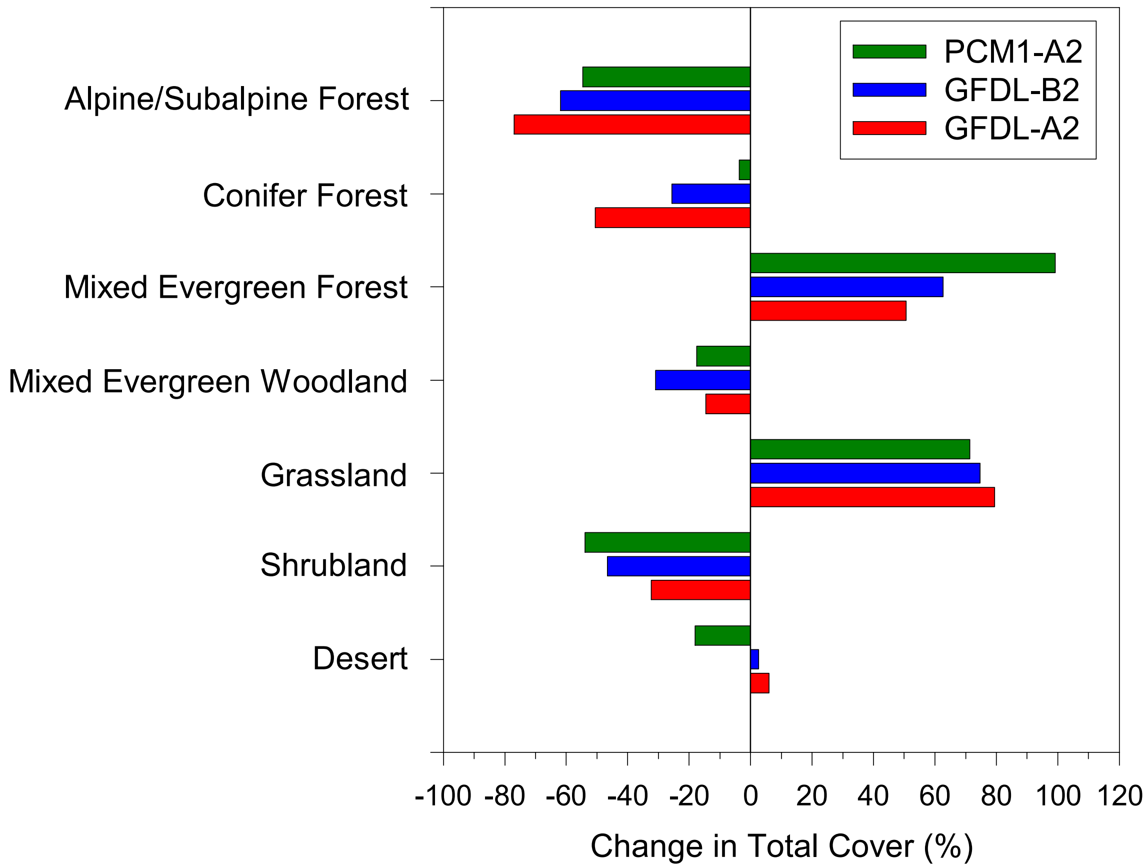

Figure 4. Percentage change in the total cover of the vegetation classes

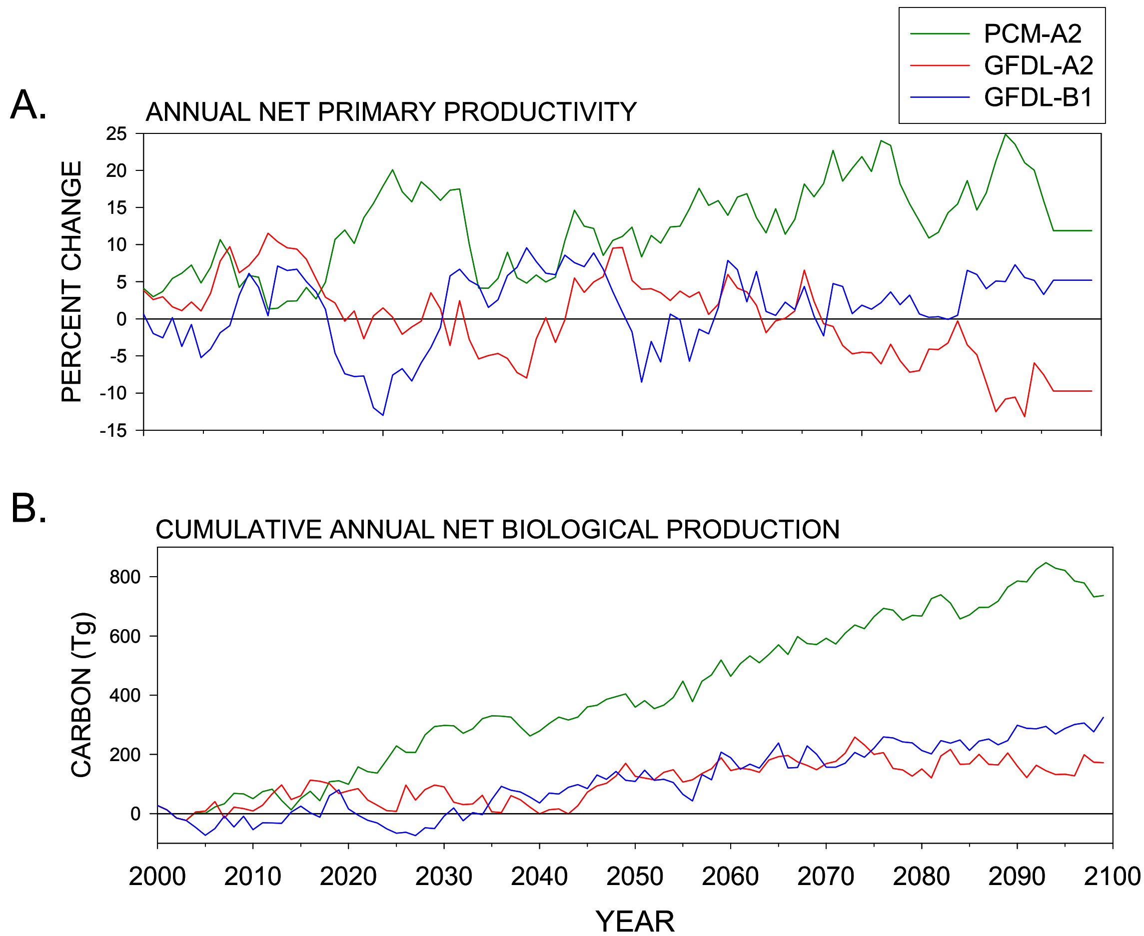

Figure 5. (A) percent change in annual net primary production (NPP) relative to simulated mean annual NPP for the 1895–2003 historical period, and (B) cumulative net biological production over the future period. NPP trends have been smoothed using a 10-year running average.

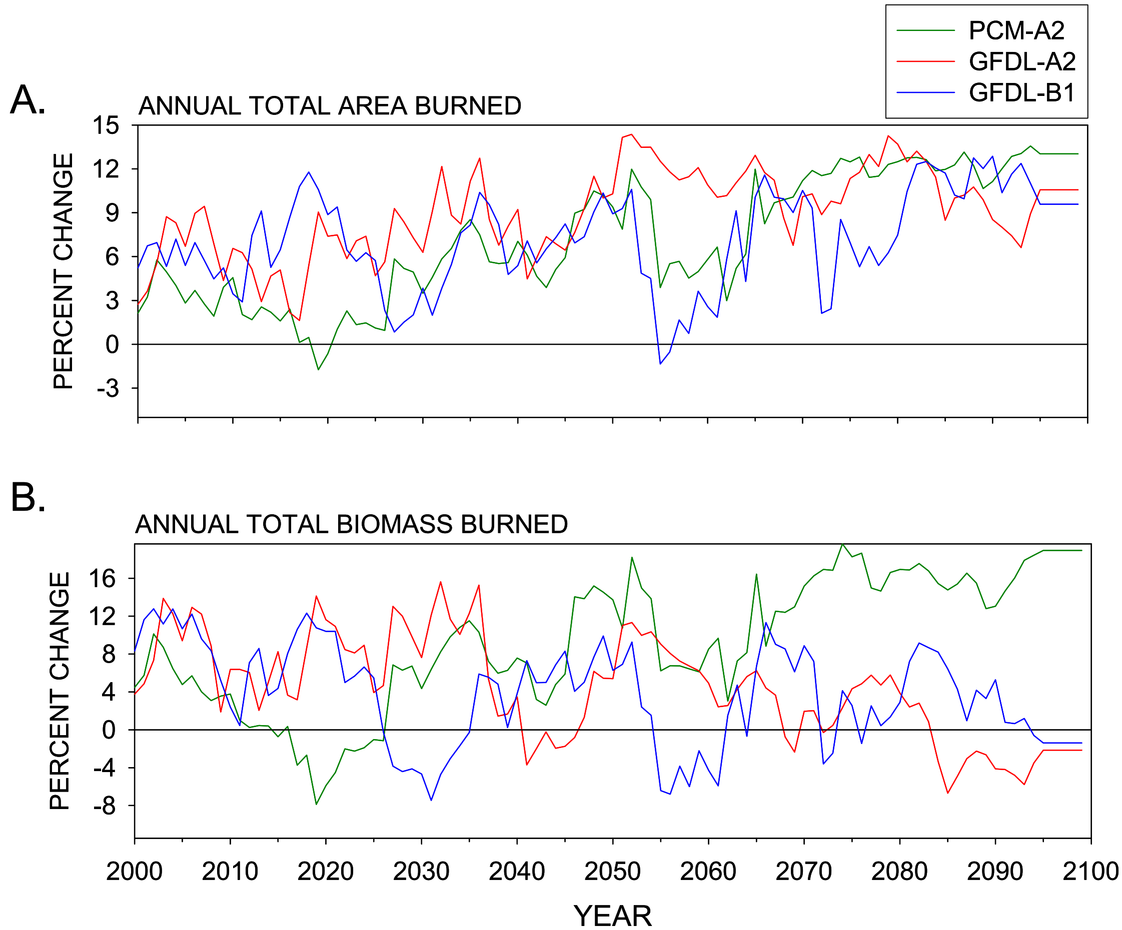

Figure 6. (A) percent change in annual total area burned relative to the simulated mean annual total area burned for the 1895–2003 historical period, and (B) percent change in annual total biomass consumed relative to the simulated mean annual biomass consumed for the historical period. All trend lines have been smoothed using a 10-year running average.

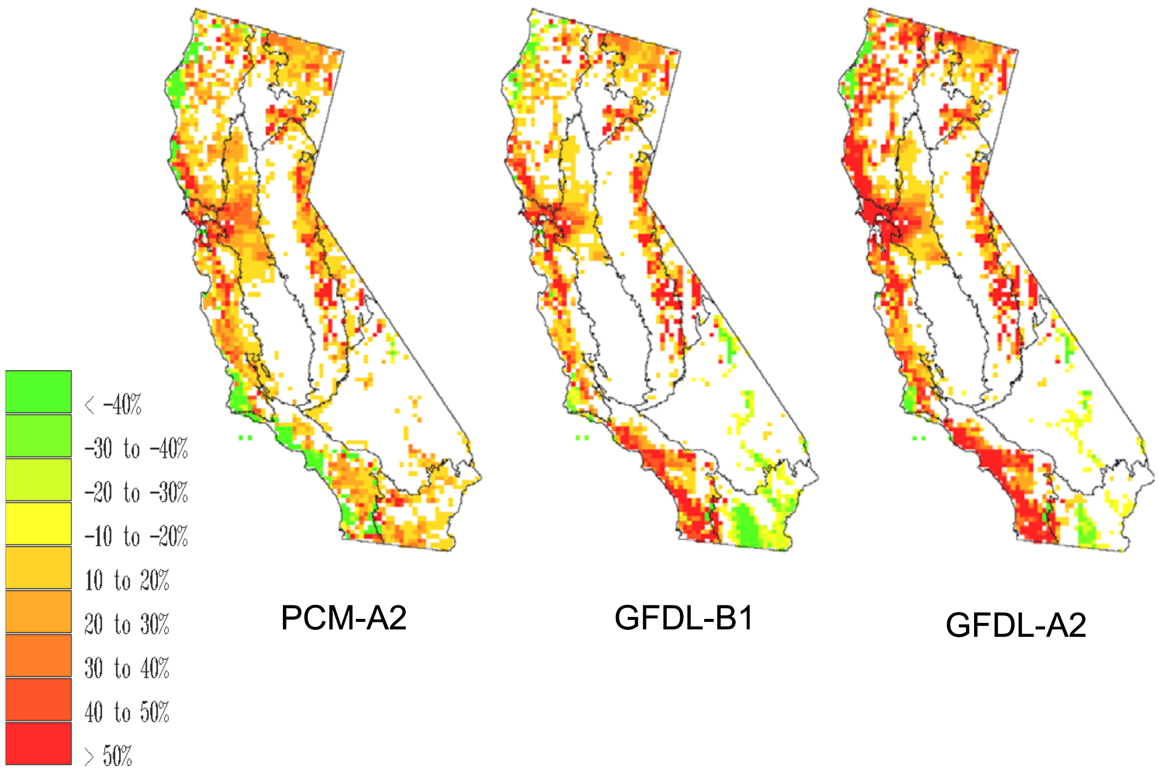

Figure 7. Percent change in mean annual area burned for the 2050–2099 future period relative to the mean annual area burned for the historical period (1895–2003)